



## Reliability Based Optimization of Fire Protection

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# Reliability Based Optimization of Fire Protection

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## 1. Introduction

It is well known that fire is one of the major risks of serious damage or total loss of several types of structures such as nuclear installations, buildings, offshore platforms/topsides etc. This paper presents a methodology and software for reliability based optimization of the layout of passive fire protection (PFP) of firewalls and structural members. The paper is partly based on research performed within the EU supported research project B/E-4359 "*Optimised Fire Safety of Offshore Structures*" and partly on research supported by the Danish Technical Research Council (see Thoft-Christensen [1]. Special emphasis is put on the optimization software developed within the project.

Optimisation of the fire safety of a structure like an offshore platform involves optimisation of the passive fire protection, the active fire protection system, the safety equipment, the primary and secondary structural elements, the Temporary Safe Refuge, and Escape, Evacuation and Rescue Systems. However, such a complex optimization is not realistic with the current knowledge in this field.

Since PFP is very important for the fire safety of most structures this paper focuses on the optimisation of PFP. The overall optimisation problem formulated is to minimise the cost of the PFP with constraints on the minimum acceptable safety. The design variables are the type and amount of PFP and to some extent whether PFP is to be applied to walls/structural elements or not. Uncertainties are related to the fire loading, the thermal properties of the structural steel, the insulation and to material and strength parameters.

Methodologies for optimisation of PFP and corresponding computer programs have been developed. A program OPTIWALL [2] for optimisation of the PFP on firewalls and a program OPTIBEAM [3] for optimisation of PFP on structural members have been implemented.

The program OPTIWALL performs deterministic and reliability-based optimisation of the PFP attached to firewalls. The program determines the optimal thickness and material for the PFP for one or more firewalls subjected to heat loads while minimising the cost.

The program OPTIBEAM performs deterministic and reliability-based optimisation of the PFP attached to structural members (beams or columns). The program determines the optimal thickness (and material) for the PFP for one or more scenarios while minimising the cost of PFP.

Additionally, the effect of other mitigation measures such as deluge/sprinkler systems can be taken into account. In both programs constraints are related to the reliability of the

wall/structural members using limit-states on the maximum temperature and on general buckling/yielding failure using API, AISC and ECCS models.

## 2. Optimal Deterministic Structural Design Formulations

Structural optimization problems are generally characterised by

- a large number of design variables (structural dimensions(e.g. cross section parameters), shape variables (e.g. shape of steel plates) and topological variables)
- simple objective functions (e.g. the cost or the weight of the structure)
- indirect constraint functions. The constraints are usually complicated because they are often given indirectly through the solution of large finite element problems. If the constraints are related to reliability measures such as element or systems reliability indices then the constraints are even more complicated from a computational point of view.

In classical deterministic structural design the optimization problem is usually formulated as

$$\begin{aligned} \min_{\bar{z}} \quad & C(\bar{z}) \\ \text{s.t.} \quad & h_i(\bar{z}) = 0 \quad i = 1, \dots, m_e \\ & g_i(\bar{z}) \leq 0 \quad i = m_e + 1, \dots, m_c \\ & z_i^{\min} \leq z_i \leq z_i^{\max} \quad i = 1, \dots, N \end{aligned} \quad (1)$$

where  $\bar{z}^T = (z_1, \dots, z_N)$  are the design (optimization) variables.  $C$  is the objective function and  $g_i, h_i, i = 1, \dots, m_c$  the constraints.

The optimization variables are usually related to parameters defining the geometry of the structure (for example the cross section of a beam or the thickness of a plate) and coordinates defining the geometry (shape) of the structural system. The objective function is often chosen as the weight, the cost or the safety of the structure. The equality constraints in (1) can be used to model design constraints (e.g. constraints on the geometrical quantities) and to relate the load on the structure to the response (e.g. finite element equations). The inequality constraints in (1) ensure that the response characteristics such as displacements and stresses do not exceed codified values. Determination of the inequality constraints usually includes finite element analysis of the structural system. The inequality constraints can also include general design requirements for the design variables. The last mentioned constraints in (1) are so-called simple constraints

Generally the optimization problem (1) is non-linear and non-convex.

## 3. Optimal Reliability Based Structural Design Formulations

In reliability based structural optimization a number of different formulations can be used. In the first formulation an element reliability index based design problem is formulated, see Sørensen & Thoft-Christensen [4], Frangopol [5] and Murotsu et al. [6].

$$\begin{aligned}
& \min_z C(\bar{z}) \\
& s.t. \quad \beta_i(\bar{z}) \geq \beta_i^{\min} \quad i = 1, \dots, M \\
& \quad \quad B_i(\bar{z}) \geq 0 \quad i = 1, \dots, m \\
& \quad \quad z_i^{\min} \leq z_i \leq z_i^{\max} \quad i = 1, \dots, N
\end{aligned} \tag{2}$$

where  $\beta_i$  is the reliability index of structural element  $i$ , see e.g. Thoft-Christensen & Baker [7].  $B_i$  is a deterministic function.

Different formulations of the objective function  $C$  in (2) have been proposed. The most simple choice is to use the structural weight but other alternatives exist. A much more complicated objective function is the total expected costs during the lifetime of the structure. The total expected costs include initial cost, inspection cost and repair costs, failure costs and removal cost.

A second formulation is based on the system reliability index, see Thoft-Christensen & Murotsu [8].

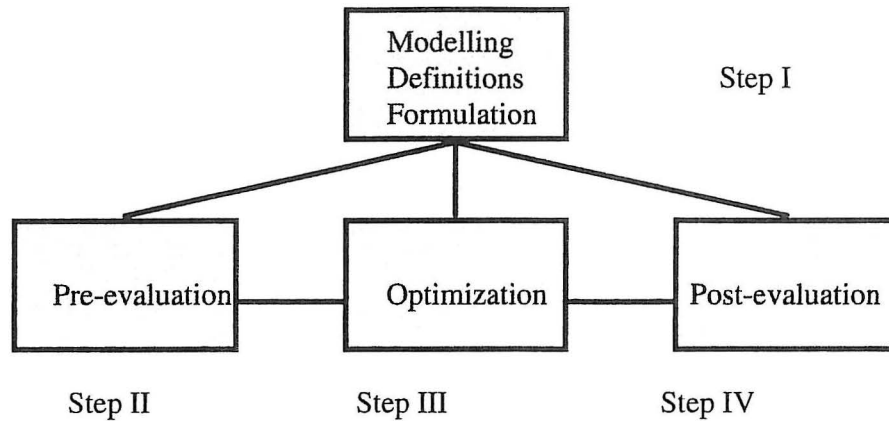
$$\begin{aligned}
& \min_z C(\bar{z}) \\
& s.t. \quad \beta^s(\bar{z}) \geq \beta^{\min} \quad i = 1, \dots, M \\
& \quad \quad B_i(\bar{z}) \geq 0 \quad i = 1, \dots, m \\
& \quad \quad z_i^{\min} \leq z_i \leq z_i^{\max} \quad i = 1, \dots, N
\end{aligned} \tag{3}$$

where  $\beta^s$  is the system reliability index for a series system.

An efficient optimization algorithm has been developed by Schittkowski [9].

#### 4. Architecture of an Optimization System

In this paper only optimization of PFP is considered. The layout of the structure is assumed given (location of the firewalls is given and the structural elements protected using PFP are identified). The design variables are the amounts and types of PFP. The optimization problem is then to minimize the cost of the PFP with requirements on the minimum acceptable safety. The optimization methodology proposed here consists of a number of steps. Not all steps are obligatory.



*Figure 1. Architecture of the optimization system*

## **5. Step I. Modelling, Definitions and Formulation**

This first step consists of a number of actions such as:

- selection of the structural model,
- definition of a FEM model,
- grouping of structural elements,
- definition of fire scenarios,
- definition of failure modes and corresponding limit states and
- the stochastic modelling.

## **6. Step II. Pre-Evaluation**

This pre-evaluation step is a very useful tool. In many cases the optimization of PFP can be performed using only the pre-evaluation modules. In the pre-evaluation the following actions are performed:

- a FEM analysis of the structure is performed and the potential failure modes are evaluated,
- the structure is modified if one or more limit states are violated,
- sensitivity analysis parameters are defined,
- a sensitivity analysis is performed to obtain a feasible design without reanalysis of the structure,
- design variables are added or removed based on the results of the sensitivity analysis,
- a corresponding, deterministic optimization problem is formulated (optional) and
- the deterministic optimization problem is solved,
- the reliability index and its derivatives are calculated so that limit states, stochastic variables etc. may be deleted/added.

## **7. Step III. Optimization**

This step is the main step, but in some cases it is not used since it may be very time consuming. At this step the following actions are performed:

- the reliability based optimization problem is defined (design variables, objective function and constraints),
- the reliability based optimization problem is solved.

## 8. Step IV. Post Evaluation

At this step the following actions are performed:

- the optimization results may be modified, e.g. rounding up of some design variables to the nearest allowable value,
- the optimization results are evaluated to ensure that all assumptions are valid, a new grouping of elements or the use of new PFP material may be done and a new optimization performed, i.e. the optimization is repeated from the beginning.

## 9. Formulation of the Optimization Problem

The reliability based optimization problem solved in this paper is formulated in the following way

$$\begin{aligned}
 & \min_{\bar{b}} C(\bar{b}) \\
 & \bar{b}^T = (b_1, \dots, b_n) \\
 & s.t. \quad \beta_j(\bar{b}, \bar{x}, T, s_i) \geq \beta_j^{\min} \quad j = 1, \dots, M \\
 & \quad \beta^{sys}(\bar{b}, \bar{x}, T, s_i) \geq \beta^{sys, \min} \\
 & \quad b_i^{\min} \leq b_i \leq b_i^{\max} \quad i = 1, \dots, n
 \end{aligned} \tag{4}$$

where  $C$  is the objective function (cost function) and  $\bar{b}^T = (b_1, \dots, b_n)$  are the design variables.  $s_i$  is fire scenario  $i$  and  $T$  is a reference time. The reference time could be the time where the fire is maximum or the time to evacuate all personnel.  $\bar{x}$  is a vector of stochastic variables,  $M$  is the number of constraints and  $n$  is the number of design variables. The solution to this problem is  $\bar{b}_{opt}^i$  where superscript " $i$ " indicates scenario  $i$ . Problem (4) is solved for all  $N$  scenarios and as the final optimal solution the maximum value for each design variable is used.

Optimization of PFP on the topside is divided into two parts:

- optimization of PFP on non-structural parts (firewalls) using the software package OPTIWALL
- optimization of PFP on structural members using the software package OPTIBEAM,

The programs OPTIWALL and OPTIBEAM are able to find optimal PFP for both firewalls and structural members subjected to pool and/or jet fires.

## 10. The Software Package OPTIWALL

The program OPTIWALL combines a fire analysis program, a reliability assessment program for reliability evaluation of firewalls subjected to fire (consisting of a program for calculation



of heat transfer to firewalls and a program for reliability evaluation), and a non-linear optimization program.

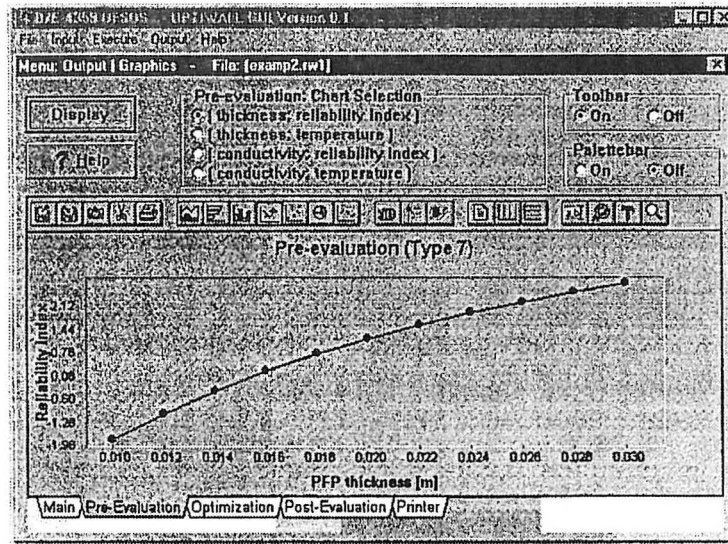


Figure 2. OPTIWALL. Pre-Evaluation: Reliability index as a function of the PFP thickness.

It is assumed that all firewalls have insulation material, that the geometry of the fire wall is constant and that only insulation on the hot side of the firewall is optimized. There are only two design variables for a firewall, namely the thermal conductivity of the PFP material and the thickness of the insulation material. The objective function is the cost of the PFP modelled as a function of the thickness and of the thermal conductivity and a constant term related to the installation. A constraint is in the deterministic case imposed on the temperature at the interior face of the insulation, which at the reference time  $T$  (60 minutes for A60 walls and 90 minutes

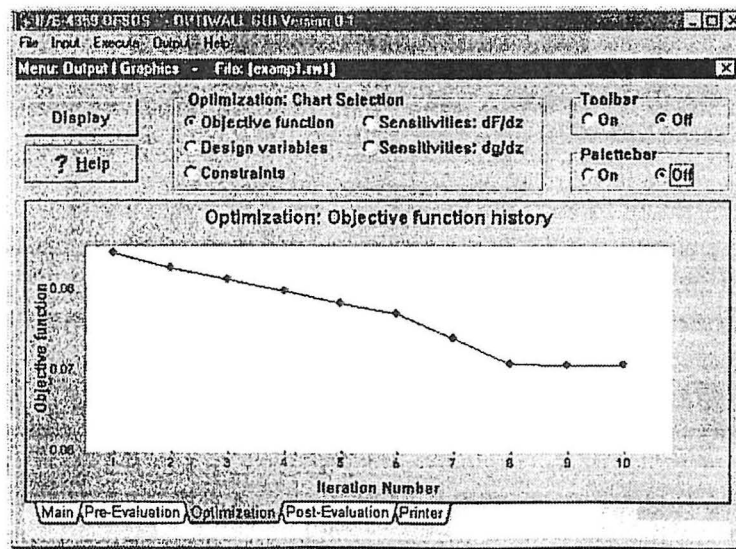


Figure 3. OPTIWALL. Optimization: History of the objective function.

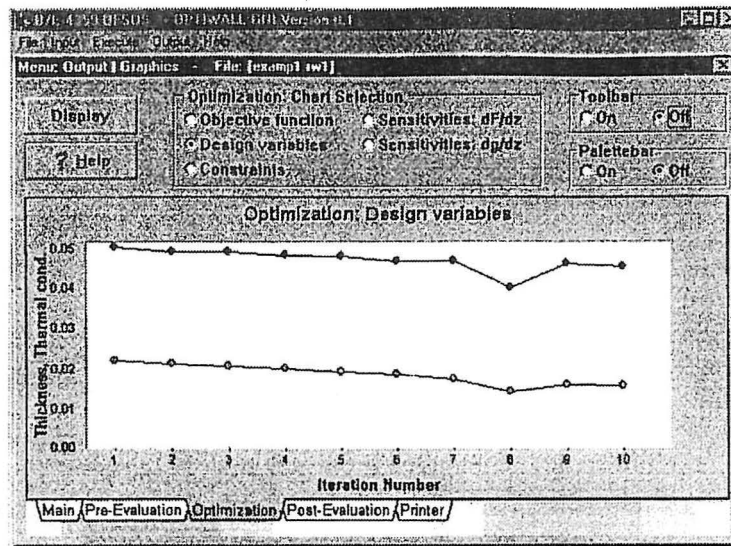


Figure 4. OPTIWALL. Post-Evaluation: History of the design variables.

for A90 walls) must be lower than some specified limit state temperature. In the reliability based formulation the constraints are related to the probability that the temperature in the firewall exceeds a limit value.

In figures 2, 3, and 4 output screens from using OPTIWALL, namely the reliability index as function of the PFP thickness, the history of the objective function, and the history of the design variables, are shown for illustration.

## 9. The Software Package OPTIBEAM

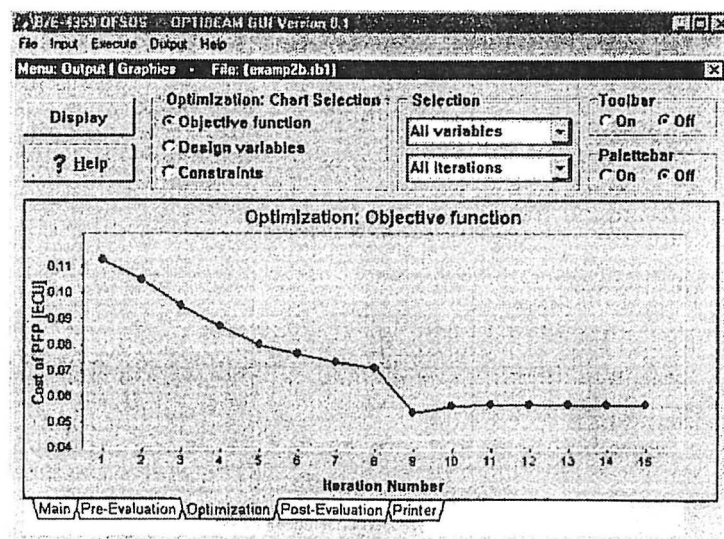


Figure 5. OPTIBEAM. Optimization: History of the objective function.

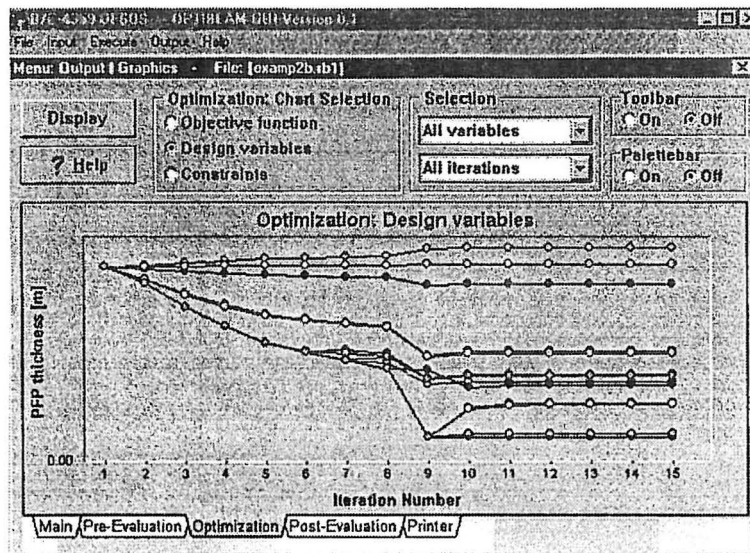


Figure 6. OPTIBeam. Optimization: History of design variables.

The OPTIBeam program combines the modules for reliability assessment with the modules for optimization. OPTIBeam performs deterministic and reliability based optimization of PFP attached to structural members. The design variables are the thickness of the PFP on topside beams/columns. Since the number of structural elements on a standard topside structure may be quite large, grouping the design variables into a number of groups is implemented in OPTIBeam in order to reduce the number of design variables. In order to take into account the effect of other mitigation measures (AFP, improved lay-out, etc.) a third term may be included in the objective function. The objective function is the sum of the total cost of PFP and the expected failure costs. It is assumed the expected failure costs are proportional to the initial cost of the structure without PFP. Constraints are related to a limiting temperature failure criterion or to member failure by buckling/yielding (using the API/AISC model or the ECCS model).

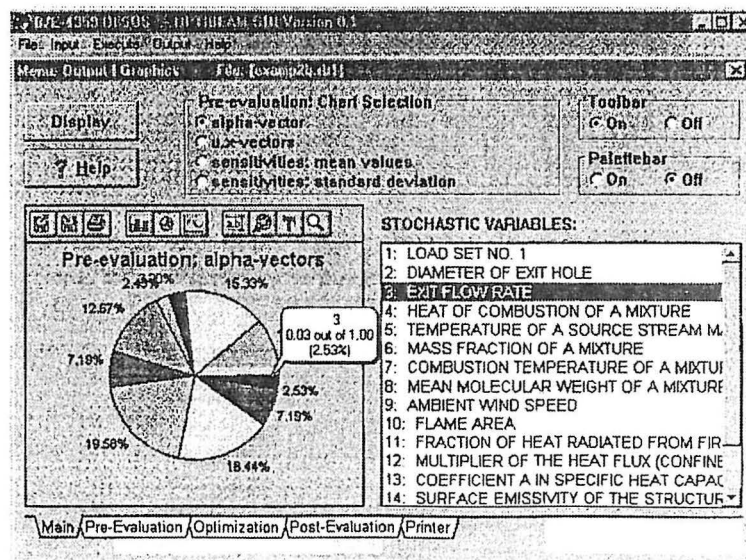


Figure 7. OPTIBeam. Post-Evaluation. Sensitivity Analysis.



In figures 5, 6, and 7 output screens from using OPTIBEAM, namely the history of the objective function, the history of the design variables, and a sensitivity analysis, are shown for illustration.

## 10. Conclusions

Major achievements in this paper with regard to reliability based optimization can be summarized as:

- A formulation of reliability based optimization problems for both PFP on firewalls and structural members has been specified.
- A methodology and specifications for prototype software for PFP optimization including pre- and post-evaluation of firewalls and structural members have been developed.
- A DOS program OPTIWALL for optimization PFP (including pre- and post-evaluation) of PFP on firewalls has been implemented and tested.
- A DOS program OPTIBEAM for optimization PFP (including pre- and post-evaluation) of PFP on structural members has been implemented and tested.
- A Windows GUI for OPTIWALL and OPTIBEAM has been developed.

## 11. Acknowledgement

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## 12. References

- [1] Thoft-Christensen, P. *Reliability Based Optimization of Passive Fire Protection on Offshore Topsides*. IFIP TC7 Conference, Detroit, July 1997.
- [2] OPTIWALL, CSRsoftware, CSRconsult, P.O. Box 218, DK-9000 Aalborg, Denmark.
- [3] OPTIBEAM, CSRsoftware, CSRconsult, P.O. Box 218, DK-9000 Aalborg, Denmark.
- [4] Sørensen, J.D. & P. Thoft-Christensen. *Structural Optimization with Reliability Constraints*. Proceedings 12<sup>th</sup> IFIP Conference on System Modeling and Optimization, Springer Verlag, 1986, pp. 876-885.
- [5] Frangopol, D. M. *Sensitivity of Reliability-Based Optimum Design*. ASCE, Journal of Structural Engineering, Vol. 111, No.8, 1985.
- [6] Murotsu, Y. , M.Kishi, H.Okada, M.Yonezawa & K.Taguchi. *Probabilistic Optimum Design of Frame Structure*. In P.Thoft-Christensen (editor): System Reliability and Optimization, Springer Verlag, 1984, pp.545-554.
- [7] Thoft-Christensen, P. & M.J. Baker. *Structural Reliability Theory and Its Applications*. Springer Verlag, 1982.
- [8] Thoft-Christensen, P. & Y. Murotsu. *Application of Structural Systems Reliability Theory*. Springer Verlag, 1986.
- [9] Schittkowski, K. *NLPQL. A FORTRAN Subroutine Solving Constrained Non Linear Programming Problems*. Annals of Operations Research, 1986.





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